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FINAL REPORT NEL 108

May 15th 1988

DESIGN, CONSTRUCTION AND FIELD TRIALS OF A 5 kW VERTICAL AXIS HYDRO TURBINE FOR "OFF GRID" RIVER INSTALLATIONS (TOR 5 VAHT)

FOR

ENERGY MINES AND RESOURCES - CANADA

DSS Contract No. 51SZ. 23216-6-6169

BY

NOVA ENERGY LIMITED

P.O. BOX 635

DARTMOUTH, NOVA SCOTIA.

B2Y 3Y9

90-01357/

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CONTRACT DIRECTORY INFORMATION SUMMARY

Contractor:	Nova Energy Limited P.O. Box 635, Dartmouth, Nova Scotia. B2Y 3Y9
Title:	Design, Construction and Field Trials of a 5 kW Vertical Axis Hydro Turbine for "Off Grid" River Installations (TOR 5 VAHT). Barry V. Davis, President. (902) 466-5854
Sponsor:	Energy Mines and Resources - Canada.
Contract No.	DSS 51Z. 23216-6-6169
Objectives:	To demonstrate the technology and establish the performance characteristics of a small "Off Grid" floating free stream VAHT. To design the turbine to meet a perceived market need. To establish a design that is suitable for economic production.
Work Actually Accomplished:	A 5kW VAHT has been designed and built as required by the contract, and field trials conducted. No functional or operational problems were encountered during the trials. The field trials showed the need for larger blades. When these were installed the trials results defined the operational envelope of the unit, and showed a performance envelope similar to that predicted by model tests. Based on the trials data analysis, 5 kW will be produced with the turbine running at 54 RPM in a freestream current of 2.35 m/sec. i.e 4.56 knots.
Project Status:	Nova Energy intends to manufacture and market the TOR-5 VAHT units after further extended model trials, demonstrations, market studies and production modifications have been completed. A proposal to EMR for further field trials and demonstrations across Canada will follow, to capitilize on the success of this contract.
NOTE:	The TOR 5 design is believed to have unique Patentable features.

Contract Duration:	20 Months
Total Cost To The Crown:	$54,718.00
Contractors Contribution:	$18,239.00
Total Cost:	$72,957.00

ACKNOWLEDGEMENTS

Funding for this project was provided by the Panel of Energy Research and Development, Office of Energy Research and Development, Department of Energy, Mines and Resources, Canada.

Nova Energy also wishes to acknowledge the continuing support and advice of Mr. Tony Tung, Technology Coordinator, Renewable Energy Division, Department of Energy, Mines and Resources, Canada, Dr. Bruce Pratte, Head of the National Research Council Hydraulics Laboratory, and Mr. Thiery Faure, Scientific Research Officer, NRC Hydraulics Laboratory.

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1. INTRODUCTION

This report describes the design, manufacture and preliminary testing of a 5 kW floating VAHT for use in tidal ocean and river installations. This work is based on the results of a preliminary design and trade off analysis carried out for the National Research Council. See Ref. 9.1. and Appendix "A".

The TOR 5 design has many unique features which are briefly described below.

a) The complete turbine assembly is mounted on a standard 18 ft. fiberglass boat hull which provides floatation, a self mooring capability, space for auxiliary equipment and maintenance personnel, a trailering capability, and self launching and propulsion to the selected site. The hull is very stable and seaworthy with extensive reserve bouyancy and floatation. Ref. Appendix "E".

b) The electrical system is an "off-grid" stand alone type with a load control governor which maintains a constant frequency of 60 Hz at 240 volts. The Thompson and Howe equipment also incorporates a load management system which maintains power to up to eight outlets, on a priority basis. The load control function is achieved by dumping excess power to a resistance load bank, which in practice would be used to heat domestic water. Refer to section 3. and Appendix "C". for Electrical system design details.

An underwater power cable runs down the mooring cable and then across the river bottom to the shore where it would be trenched ashore. The electronic load controls, switchgear and resistant heaters would be housed onshore in a weatherproof box, a utility building, or the building being serviced. There are no control wires to the turbine unit. All of the electrical system including the load simulation and load dump resistance heaters are mounted in the hull of the prototype TOR 5 unit.

c) Retraction of the rotor and frame assembly is accomplished using hand operated winches in the prototype and by means of a 12 volt electrical cable winch driving the three foot dia. retraction disc in the production units.

d) The rotor blades are readily folded once the frame is retracted over the boat. A bolting geometry has been developed which allows 4 or 6 blades and arms to be folded within the thickness of the frame. The four blades and arms fitted to the prototype are fixed, but are readily removed.

e) The rotor is self starting in the final configuration tested and a starting system is not required.

f) Because the rotor and frame assembly is mounted on a boat and also can generate high retraction loads, it is important to keep the structural weight as low as possible. This is acheived by using all aluminium construction. The marine grade aluminium has excellent corrosion resistance and all hardware is corrosion resistant stainless steel.

g) The prototype rotor has a hand operated band brake which acts on the low speed flexible coupling housing. The rotor can be stopped in about 10 seconds when under full load. The production rotor will have an electrically operated rotor brake of the "Fail Safe" type.

i) A special trailer has been made to carry and launch TOR 5 and other similar units and has worked very successfully.

j) The rotor can be readily cofigured to carry 2, 3, 4 or 6 rotor blades. The rotor shaft is easy to remove when the frame is retracted and the bearings and their housings are also easy to remove. The entire frame and machinery housing can be removed from the boat by removing two hinge pins.

k) The main rotor bearings are of the self lubricating type. They have a high PV rating and high abrasion resistance. The low speed coupling is a non lubricated type with neoprene load bearing rollers and has increasing stiffness with increasing load.

l) Mooring of the TOR 5 unit is accomplished using a galvanized steel cable bridle attached to a single steel cable which then goes upstream to a gravity anchor or convenient pylon or bridge pier.

Design details for the TOR 5 are given in Section 2.

2. DESIGN - ROTOR, HULL AND MACHINERY

The design of the TOR-5 VAHT is based on the preliminary design and performance details set out in Proposal NEL-108 and on the design work and concepts established in Ref. 9.1.

The entire frame structure was fabricated using rivetted and bolted aluminium sheet (mostly 11 s.w.g.) and aluminium structural extrusions. The main reasons for using aluminium were weight reduction, reduced retraction loads, corrosion resistance, ease of fabrication and handling, and elimination of warping problems experienced when welding light structures.

The initial trials with the unit in a tidal flow and in later towing trials showed that the original "Vega" foil section extrusions were not suited to the installation because the chord was too small and consequently the solidity was too low. i.e. blade chord of 75 mm and solidity of 0.33 with four blades and 0.49 with six blades. (This rotor is called the "V" Series). Thus the rotor was rebuilt using the foil blade extrusions remaining from the "B1" and "B2" projects. i.e. blade chord of 197 mm and solidity of 0.86 with four blades. (This rotor is called the "B" series).

The approximate weight of the complete turbine frame and rotor assembly supported by the transom hinges is 482 kg. including gearbox and generator. The centre of gravity of this unit is about 80 cm. below the hinge line, giving a maximum retraction load of 843 kg. The winch capacity is 1400 kg. The drag load on the rotor at runaway in a 3 m/sec. current is about 1900 kg., giving a load on the drag cables of 1200 kg. each, and a vertical load on the hinges of 680 kg. each. In general all factors of safety are over five and most structural elements are designed by stiffness requirements.

The rotor attachment arm hubs were originally fabricated so that the lower set of blades could be swung to line up with the upper blade set and thus allow complete retraction of the support frame structure. (i.e. "V" Series Rotor). The original frame structure and rotor assembly is shown in Photograph No. 8.1. The subsequent "B" Series Rotor used the smaller foil section extrusions for support arms and the blades on this configuration cannot be folded. This arrangement is shown in Photo's 37 to 40.

The main rotor bearings mentioned in the proposal were 6 inch dia. water lubricated "Thorden XL" bearings. These were changed to 4 inch diameter self lubricating Garlock "Gar-Fil" bearings for the final design. The Gar-Fil bearings have a polytetrafluorethylene liner with a fiberglass backing. These bearings are cheaper and have a higher load rating. They can be operated in air and are very resistant to abrasion. The smaller bearing dia. means that the rotor shaft and bearing housings are 50% smaller with consequent reductions in hydrodynamic drag and interference effects, lower weight and reduced material and fabrication costs. The smaller bearings also simplify the rotor arm attachment hubs and the flexible coupling installation. This arrangement is shown in Photo No. 8.2, which also shows the upper bearing and support housing structure.

The low speed coupling is a Dana Formsprag HD Elastomeric Coupling size HD 5. This coupling does not require lubrication and is easy to install. This coupling is shown in Photo No. 8.3.

A thrust bearing on the rotor shaft carries the rotor weight. This unit uses a Dixon self lubricating thrust bearing made from Teflon impregnated fiberglass and is shown in Photo No. 8.4. Upward movement of the rotor is restricted to 2.5 mm by a neoprene pad in the low speed coupling.

To reduce drag and turbulence from the rotor support frame, a fairing made from 2 inch black ABS water pipe slit in half is rivetted to the frame members as shown in Photo No.'s 8.5 to 8.7. These fairings also cover the flooding and draining holes in the structure, and channel water and outgassing air, while preventing clogging of the holes.

Photo No.'s 8.5 and 8.6 show the rotor structure with the "V" Series rotor blades in the operating position. These figures also show the lower bearing, the drag lugs, the gearbox and the frame to hull hinges.

Photo No.'s 8.7 and 8.8 show the "V" Series rotor blades in the retracted and stowed position. Note in Photo No. 8.8 that the retracted blades are contained within the protection of the frame structure. Photo No's 8.37 to 8.40 show the "B" Series rotor blades in their fixed operating position. Note that the frame does not fully retract and is supported by two special pipe supports. This arrangement does not detract from the trailering, launching, extension, retraction and operation of the turbine system.

Photo No. 8.9 shows the 13 mm thick aluminium machinery plate used for the prototype, with the gearbox and frame hinges mounted in place.

Jigs developed during construction of the "V" Series rotor structure are shown in Photo No. 8.10. The rotor arm welding and drilling jig and the gearbox to rotor shaft alignment jig are shown in Photo No. 8.11, and the Hull/Frame hinge jig and the rotor blade drill jig are shown in Photo No. 8.12.

The detail construction drawings are listed and enclosed in Section 7 including a drawing of the "B" Series blades, arms and hub discs. Design, Equipment and Performance Specifications are enclosed in Appendix "D". Details of the boat hull are covered in Appendix "E", and Photographs 8.17 to 8.27 and in 8.37.

3. DESIGN - ELECTRICAL SYSTEM

Several alternate stand alone electrical systems were studied for the TOR 5 Design, and are reported on in NEL - 125/86, which is enclosed as Appendix "C", together with details of the final design chosen.

The Thomson and Howe A-2 Load Control Governor was selected for the primary control of the electrical system. The operation of the governor is described in Appendix "C". The VAHT drives a Lima Electric 5 kW synchronous generator, single phase, 120-240 volt, 60 hz, SER model 3250-1233 with an aluminuim frame No. 250. This generator was selected because the Basler Voltage regulator which is built into the generator works well with the SCR type of control utilized in the Thomson and Howe Model A-2 Load Control Governor. The compatibility of the two systems has been proven in the field, reducing the possibility of problems when the complete electrical system is functioned.

The Lima Model 1233 generator is rated at 5 kw "Continuous Operation". It should be noted that generator ratings can be very misleading as some units on the market are rated at "Continuous Standby". This means that they are designed to operate intermittently to provide power in a backup mode when there is a power outage on the grid. "Continuous Standby" is not a satisfactory rating for a generator that will operate with the Thomson and Howe Load Control Governor. In this type of system the generator produces power 100% of the time. As the load on the generator varies the output is switched to the dump loads or away from the dump loads to a useful load to maintain a constant synchronous generator rpm and a 60 hz output. The generator is delivering power either to a useful load or a dump load all the time. The specifications for the generator are listed in Appendix "C".

The wiring diagram for the system is shown in Drawing NEL TOR-5-410 in section 7. The dump loads L1 and L2 give 5000 w of resistance at 240 v, while the simulated useful loads L3 to L5 give 3000 w with an extra 1000w in reserve. Photographs of the system are shown as Figure No.'s 8.13 to 8.16. Figure No. 8.13 shows the wiring of the Thomson and Howe Load Control Governor to the two dump loads L1 and L2 at the bottom of the photos. Figure No. 8.14 shows the primary shore switch box, a Federal Pioneer RH 104-8CHTS-2 with the Thomson and Howe Load Control Governor. Figure No. 8.15 shows the Federal Pioneer RH 102-4CHTS shipboard circuit breaker/switch box on the left. Figure No. 8.16 shows the simulated useful loads L3 to L5, plus a backup load (L6) which is available if required. To facilitate the TOR 5 trials and demonstrations, all the electrical equipment has been mounted inside the boat hull for the "B" Series and subsequent trials.

4. CONSTRUCTION

The main support frame for the rotor is fabricated from 11 swg 6061 aluminium and 2.25" x 1.0" x 3/16" al. channels. Al. break stem "Pop" rivets, (1/4" dia.), were used throughout the structure with stainlees steel bolts and nuts for all major joints and high stress areas. The rotor blades and arms for both the "V" Series and "B" Series Rotors and shaft details are shown in the enclosed drawings in Section 7, together with the bearings and their housings. Special jigs were made to aid in accurately welding the arms to the hubs, for drilling the arm tip attachment holes and countouring the arm to blade joints and for accurately drilling the blades. The frame and hull transom hinges were welded by a subcontractor using NEL jigs.

The drawings in Section 7 show the installation of the gearbox, generator, pulleys and handbrake. The generator mounting and belt tensioning arrangement is also shown with the structurally integrated retraction disc and machinery enclosure cover.

The major change in the production design will be the use of cast aluminium hinge structures and extruded structural members for the frame assembly.

The following photographs illustrate the main features of the prototype TOR5 VAHT construction.

Fig. 8.17. General stern view with frame retracted. One panel of machinery enclosure removed.

Fig. 8.18. Stern view showing belt drive cover in place.

Fig. 8.19. Bow view showing towing and frame drag cable attachment beam.

Fig. 8.20. Gearbox and generator installation.

Fig. 8.21. Twin "V" belt drive.

Fig. 8.22. Generator with retraction disc on right.

Fig. 8.23. Machinery plate showing belt tensioning device on the generator base.

Fig. 8.24. Detail of frame to hull hinge attachment.

Fig. 8.25. Mounting of junction box. Cable to left connects to generator. White connector on right is for cable to shore. All other electrical gear is on shore.

Fig. 8.26. Astern view showing "V" Series rotor structure in vertical position. Rotor arms would be extended with the frame in this position.

Fig. 8.27. General view with "V" Series rotor structure in vertical position .

Fig. 8.37 General view of the "B" Series rotor structure in the stowed position on the TOR 5 Hull.

5. FIELD TRIALS

"V" Series Trials - March and April 1987

A - Trials with Four 75 mm NACA 0015 Blades set at + 2 Degrees
Solidity = 0.33

The TOR 5 turbine was installed at the selected test site called "Rocky Run", located under a railway trestle at the seaward entrance to Porters Lake in Halifax County.

This site carries the runoff from Porters Lake plus a superimposed tidal flow from the Atlantic Ocean. The outflow is thus much faster than the inflow. Testing in this site proved to be both difficult and hazardous. The main reason for selecting this test site was the ability to run the turbine through its full tip speed range as the velocity changes with the tidal cycle.

When the water is deep enough to cover the turbine blades at high tide the current is too slow, while on the outgoing tide the current is fast enough but the upper quarter of the blades are out of the water, leading to extensive ventilation and severe loss of power. Thus it was not possible to develop the design power output during these trials.

Nevertheless the turbine did run and produce a small amount of 60 hertz power at 240 volts. The following system and turbine characteristics were noted.

a) The complete hull installation is very stable with more than adequate bouyancy and trim characteristics, and excellent seakeeping. No problems were encountered in extending and retracting the rotor and frame assembly and securing the rotor frame drag cables. No structural deficiencies were noted under severe operating conditions.

b) The rotor was allowed to freewheel, giving high drag loads and the maximum bow down pitching load. The hull rode high and easy under these conditions. The rotor shaft brake readily stopped the freewheeling rotor with no heat distress. The rotor bearings were trouble free and ran with minimal friction.

c) When driving the generator the rotor is very smooth with little of the characteristic VAHT torque ripple and no negative torque. There is the expected small amount of boat rocking when running under load, but this is only a degree or two. The low speed flexible coupling showed no signs of distress and worked well.

d) The frequency meter on the Thompson and Howe Load Controller held steady at 60 Hertz and the 100 watt light bulb on the resistance heater board gave off a steady light, thus indicating that the complete electrical and mechanical system was working correctly. These results show that the generator was running at 1800 rpm and the rotor at the design 73 rpm with 8 in. Dia. pulleys on the Gearbox and Generator.

e) During the preliminary trials the rotor would not start, even with the generator drive belts removed. This was traced to excess oil in the gearbox, creating considerable friction at high rpm, and to the fact that a rotor with a low solidity of 0.33, driving a synchronous generator, will not start against the gearbox, generator and drive belt resistance. Thus an auxilliary starter motor was required to run up the rotor to about half its operating rpm.

For the initial trials a makeshift 2/3 H.P. hand held induction motor, driven by a portable generator was used and worked quite well.

The following photographs show the load out, installation and testing of the TOR 5 VAHT at "Rocky Run", with the "V" series rotor installed.

Fig. 8.28. Loading TOR 5 on a boom truck at the plant.

Fig. 8.29. Unloading TOR 5 at the wharf in Three Fathom Harbour.

Fig. 8.30. TOR 5 waiting for the tide to come in.

Fig. 8.31. TOR 5 beached at Rocky Run prior to being towed under the railway trestle.

Fig. 8.32. TOR 5 in place with rotor frame being extended.

Fig. 8.33. Demonstration of stability with the frame in the vertical position.

Fig. 8.34. General view of the TOR 5 installation with the electrical equipment on the railway trestle.

Fig. 8.35. Demonstration of pitch stability with frame extended 180 Degrees.

Fig. 8.36. View looking down on TOR 5 showing details of machinery housing, frame structure, rotor assembly, retraction disc and frame to hull hinges.

"V" Series Trials - December 31st. 1987

B - Trials with Four 75 mm NACA 0015 Blades set at + 2 degrees.
Solidity = 0.33

A contract extension was obtained from EMR to carry out modifications and further trials. Based on the earlier trials experience it was decided that the best way of obtaining reliable performance data over the operating speed range would be to tow the TOR 5 unit in deep water. It was also decided that using a boom truck for moving and launching TOR 5 was very restrictive of sites and operations and also expensive. Thus a special trailer was constructed for moving and launching the unit.

It was also decided to install a 12 volt starting system with a pulley and V belt drive, a starter motor, solenoid relay and marine battery. The electrical system was refined and incorporated into two boxes to allow easy transport and set up of the equipment. About 200 KG of ballast was placed in the forepeak of the hull to balance the turbine assembly weight.

During the initial towing trials in the Northwest Arm of Halifax Harbour (By Connors Diving) the turbine would not start and on raising the turbine assembly it was found that some of the welds holding the arms to the hub had broken, and in fact one of the blade and arm assemblies was lost, and the trial was terminated.

"V" Series Trials - January 27th. 1988

C - Trials with Six 75 mm NACA 0015 Blades set at + 6 degrees.
Solidity = 0.49

Further modifications were made to improve the hub attachments by welding discs to the hub sleeves and attaching the arms with 3/8" bolts. The number of blades were increased to six and the blade incidence setting increased to six degrees. These changes were made to increase the solidity and set the incidence of the blades to the optimum setting æstablished during model trials at NRC. The blade to arm joint was MIG welded to improve strength and rigidity and the welds filed to give a smooth fillet.

Again the turbine was towed in the Northwest Arm by Connors Diving. The electrical controls and resistance banks were placed on the tow boat deck with a waterproof cable carrying power from the turbine to the tow boat. For these trials Dr. Bruce Pratte from the NRC Hydraulics Laboratory and Mr. Tony Tung from EMR were present as observers.

Towing tests were carried out at gradually increasing speeds, up to about 6 knots, with the battery powered starter motor turning over the turbine at about 40 RPM, but the rotor would not start and the trial wwas terminated.

Discussions with EMR and NRC personel, and a review of relavent model test data convinced all parties that a higher solidity ratio was required for adequate starting and operating torque to be produced by the rotor. A solidity of 0.81 for a four bladed rotor appeared to be optimum with an incidence setting of between + 2 and + 4 degrees.

"B" Series Trials - March 29th. 1988

D - Trials with Four 197 mm NACA 63/4 - 0021 Blades set at + 1.25 Degrees. Solidity = 0.86

It was not practical, from a time and cost point of view, to have new extrusions made for the blades and arms, so it was decided to use existing "B1" and "B2" 197 mm extrusions for the blades and the "VEGA" 75 mm extrusions for the arms. With a four blade arrangement this gave a solidity of 0.86 which is close to the optimum of about 0.81 indicated by model tests. An accurate layout of the blade to arm to hub geometry was made as shown in Drg No. TOR-5-360 in sect 7. It was evident from this layout that when the foil section 1/4 chord is set at zero incidence the trailing edge has a large negative incidence to the flow. (A foil section with its camber lying on the rotor radius would be an optimum shape). To minimise this effect at the leading and trailing edges requires a setting of about + 3 degrees as shown in the drawing. An alternate setting of + 1.25 degrees was also provided as there was some inication that the larger blade setting may inhibit starting. The setting of + 1.25 degrees was used for the initial trials.

It was decided to use the smaller extrusions for the arms to minimize arm drag, and also because of the findings from the "B2" experiments, which showed high interference drag at the arm to foil junction when thick foils of similar chord are used.

The electrical system layout was modified again, to simplify the set up and launching of the turbine, and to remove the possibility of straining the power cable attachments, or have the cable foul the tow boat propellor. The load dump resistance elements were mounted under the gunnels and the control box and load simulation resistors were mounted in the cuddy. A 75 amp metre, (the only range available locally), was mounted on the switchbox on the cuddy bulkhead, and used to measure the generator current to the demand load. A double pole-double throw switch was fitted to allow the ammeter to read between neutral and high on each 120 volt leg of the 240 volt generator output. A multimeter was used to measure voltage to the demand and dump load resistor banks.

The demand load can be switched to give 1, 2, 3, or 4 kW and this was done during the trials. The ammeter readings were in the 5 to 15 amp. range and the accuracy at this end of the scale proved to be very poor with only 5 amp graduations.

Thus it was decided to use the switched demand load values in the final trials data analysis. Also one of the Thompson and Howe TRIACs in the load dump circuit failed so that load was being dumped to half the dump load resistors. i.e. 3000 kW instead of 6000 kW. This was accounted for in the data analysis.

The additional weight of the larger rotor made extension and retraction very difficult and better quality cable handling gear is required for future trials. The athwartship support channel that carries the rotor drag cable loads was removed and replaced with gunnel structures, which are also mounted to the deck, and are used to attach lifting cables which allow the complete turbine system to be hoisted off the trailer and put on its shop dolly.

On commencing towing the rotor started at about 3 knots, without the starter motor engaged, and with the electrical generating system engaged. The velocity was measured using a calibrated Texas Instruments Loran "C" system and runs were made at various speeds while recording amperage, demand load voltage, frequency and percentage dump load with various amounts of switched demand load. The results of these tests are tabulated in Table No. 1 in Section 9.

Sufficient runs were carried out to verify the performance and demonstrate that all systems worked correctly. Some modifications are required before extended testing can be undertaken, but all the essential elements of the design and their correct functioning were demonstrated and are discussed in Section 6.

The boat proved to be stable under adverse conditions, even when the rotor frame was in the vertical retraction position. Under tow the boat was well behaved and slightly stern down due to the weight of the turbine and frame. When the rotor was running the additional drag lifted the stern so that the hull ran level. The ride was very steady with a minor feel of surging underfoot.

The following photographs show installation details of the four large B2 blades and the rotor frame transport support struts.

Fig. 8.37 General stern view showing the final configuration of TOR 5 and its trailer.

Fig. 8.38 Rotor frame, rotor with large blades and frame support struts.

Fig. 8.39 View showing small arms and large blades.

Fig. 8.40 View showing welding of the arm support discs to the hubs and the bolting of the arms to the discs.

6.1 CONCLUSIONS

6.1.1 General Comments:-

The trials objectives were met, and successfully demonstrated that the mechanical, structural and hydrodynamic design goals were achieved. The final test runs demonstrated reasonable agreement with models tested in the NRC Water Flume using the same foil section. Powerful and repeatable starting capability was demonstrated with the four blade rotor operating at full scale Reynolds number.

The electrical system worked as specified, and the reduction in torque ripple effects was much better than expected. The Thompson and Howe load controller monitors frequency output 20 times per second and this sample rate is more than adequate to hold the frequecy steady and also significantly reduces the rotor torque fluctuation effects on the support structure. There was no indication of negative torque during any of the trial runs. There were no visible boat motions, although a slight variation in surge was noted as each blade produced power. This effect was not large enough to show up as tow rope motion.

Various aspects of the design are described in more detail below.

6.1.2 Operational Characteristics:-

A trailer was built to carry the TOR 5 turbine. The trailer was designed as a general purpose unit with a flat bed made of 2" x 6" wood planks and a keel slot to accomodate the boat hull. High density polyethelene runners were used to facilitate launching and retrieval. The trailer can be tilted relative to the tow bar to aid in launch and retrieval. The running gear and frame are designed for an all up load of 6000 lb. and the trailer weighs about 1000 lb. The trailer towed very well, both alone and with a variety of loads including a fork lift truck and the B2 aluminium duct sides as well as the fully equipped boat and turbine assembly.
However this is a marginal load for a Suburban truck, even with a towing package including an oil intercooler, and a 3/4 ton truck equipped for towing is recommended. Also while the trailer frame is structurally adequate it should be equipped with a four wheel system with electric brakes. This would allow smaller wheels and a larger footprint for soft ground and easier launching, plus a lighter tongue load. The trailer was designed for frequent immersion in fresh and salt water, thus the taillight assemblies can be removed during launching and retrieval, and the steel structural members are treated with anti-corrosion paint.

Extension and retraction of the rotor support frame is acheived using a 3 ft. dia. disc which is grooved to carry 5/16" steel cables that pass under transom pulleys and run along the deck to two hand operated winches. By keeping the cables in tension as the rotor frame extends over top dead centre the load is transfered from the "UP" winch to the "DOWN" winch.

Once the rotor frame is fully extended against its stops the drag cables are attached and tensioned. This procedure and the locally manufactured equipment worked smoothly, but the mechanical elements of the offshore manufactured winches quickly deteriorated and became hazardous to use even at half their rated load. For further trials these winches must be replaced by North American units which are much more durable and reliable.

With the unit launched and floating, the rotor frame is extended to the horizontal astern position until the unit is towed to deep water. The boat is stable with the rotor frame in the vertical position, but it is not adviseable to extend the frame if a strong wind is blowing and/or waves over 1 ft. are running. The large B2 blades add about 200 lb. to the rotor and frame weight which decreases the stability margin. Proposed modifications would reduce the weight of the blades and the rotor shaft and improve the stability margin. Under tow with the rotor stopped the boat is steady in yaw, pitch and roll and sits bow high due to the weight of the turbine assembly. Once the rotor starts the stern rises until the deck is essentially level and water on the deck tends to run forward. Again the boat was steady in yaw, pitch and roll, with a minor feeling of surge motion. Some form of outboard motor propulsion is needed for handling the boat in rivers or adverse weather conditions. Generally a tow boat is too large to come near to shore, and for most rivers a tow boat is probably not available. Two 10 H.P. outboard units with low pitch propellors would give good controll and adequate thrust for all likely sites.

6.1.3 Mechanical Equipment:-

The gearbox oil was changed to a lighter grade for winter operation (SAE 90) and care taken to ensure the sump was no more than 1/3 rd. full, to give minimal gearbox friction during rotor startup. On open water with a stiff wind the gearbox may remain cold even with extended running. In hot summer weather a temperature controlled relay and magnetically coupled pulley driven fan may be required for cooling. Further work needs to be done on control of the gearbox environment, probably by insulating the machinery enclosure and providing for automatic forced ventilation in hot weather.

The pulley system, generator belt tension system, gearbox sump air breather valve, rotor support frame hinges, elastomeric coupling, water lubricated thrust bearing, hand operated band brake and the retraction disc, retraction cables and transom cable guide pulleys all functioned smoothly and reliably and changes are not anticipated.

Problems with the retraction winches are covered in section 6.1.2. The rotor bearings appear to be satisfactory, but more extended operation time is required to prove their durability.
During the initial trials the lower bearing was scored when it was forced into the sand and gravel bottom while running. Since these bearings are self lubricating, simple urethane anti-contamination seals may be required.

Because the rotor shaft is mild steel it tends to rust where the bearings run, as these areas cannot be treated with anti corrosion paint. It is proposed to use stainless steel sleeves as the bearing journals and an aluminium rotor shaft to avoid this problem. (Refer to Section 6.1.4).

6.1.4 Structure and Materials:-

No structural or corrosion problems were experienced with the rotor frame, the gearbox and generator mounting, the retraction disc, or any of the related fittings.

During the initial "V" Series towing trials some of the rotor arm to hub welds broke (Ref. Drg. No. TOR 5 - 300 Sheet 2 - Issue 2) due to poor welding by the subcontractor. For subsequent trials 14" dia. x 3/8" discs were welded to the hubs and the arms bolted in place as shown in Drg. No. TOR 5 - 300 Sheet 3 - Issue 1, and Photo No. 40. in Section 8. To ensure more reliable welds Nova Energy introduced MIG welding in its shop, and all the aluminium welding on the rotor assembly was done with MIG welding equipment.
To reduce the weight of the rotor assembly and avoid corrosion problems, it is proposed that the mild steel rotor shaft be replaced with an aluminium shaft, with stainless steel sleeves for the bearing journals. If the NACA 63/4 -0021 sections are replaced with NACA 0015 sections this will reduce the foil weight by about 30% These changes will reduce the retraction loads and improve stability during retraction and extension of the rotor and frame assembly.

6.1.5 Electrical System:-

Apart from the addition of an ammeter to the electrical system, no changes were required to the original design, although the controls, switchgear and resistance banks have been repackaged in the boat hull to streamline handling and for operational convenience. The failure of one of the TRIACs in the Thompson and Howe load dump circuit is described in Section 5 on page 14. Since the dump load was always less than half the dump load heater bank capacity, this should not have any effect on the test results. The Lima Electric Company synchronous generator and voltage control system worked as specified.

6.1.6 Hull and Fittings:-

The RF 18 hull has proven to be rugged, strong and seaworthy, and easily meets all the requirements for mounting and transporting the turbine assembly. The flat keel lines make it easy to trailer and launch in shallow water without rollers and their attendant problems. The high density polyethalene runners, frame stops on the transom, trailer extension to protect the machinery enclosure and retraction disc, hinge support brackets and overall configuration can be seen in Photo No. 37. The frame support struts and drag cable attachments can be seen in Photo No. 38.

6.1.7 Performance

Measurements of the amperage, voltage, frequency and percentage of load being dumped by the load controller were recorded for a range of towing speeds during the trials on March 29th. 1988. The analysis of this data is based on the following equations.

Eqn. 1. Power P = Ck x 0.5 x p x At x Va^3 x Nt (Ref. App."G")

Where Ck = Power Coefficient
p = Density of Water in Slugs/Cubic ft.
At = Turbine Area in Sq. Ft. = 2 x R x H
R = Rotor Radius = 3 ft.
H = Rotor Height = 5 ft.
Va = Free Stream Velocity in ft./second
Nt = 0.70 (based on 90% mechanical efficiency and 78% generator efficiency).

Eqn. 2. Tip Speed Ratio TSR = 2 x PI x N x R / (60 X Va)
(Ref. App. "G" for standard nomenclature and equations)

PI = 3.1416 and N = R.P.M
Thus TSR = 0.31416 X N / Va

Eqn. 3. Power in kW = Demand Load in kW + 3 x % Dump Load
(Based on 3 kW resistance load dump)

N = (1805/25.06) x 8/10 x Hz/60

Hz = Electrical System Frequency
ft./sec = Knots x 1.69
metres/sec = Knots x 0.5153
kW = 0.02848 x Ck x Va^3 and Ck = 35.108 x kW/Va^3
Generator Pulley P.C.D. = 8"
Generator RPM = 1805 x Hz/60
Gearbox Ratio = 25.06 to 1
Gearbox Pulley P.C.D. = 10"

The trials data and calculation of Tip Speed Ratios, Generator Outputs and Power Coefficients are presented in Table No. 1. of Section 9. Figure No. 1 presents a plot of Ck versus T.S.R. from the towing trials, with a 10" drive pulley, and compares it with test data from the NRC water flume. This data was then used to calculate the performance over the operating current speed range for RPM's of 58 and 54 and is presented in Table No. 2 of Section 10. Figure No. 2 shows the performance of TOR 5, based on the trials data, for 58 RPM (10" pulley) and 54 RPM (10.75'" Pulley), for the NACA 63/4-0021 foil section. It can be seen that the design point of 5 kW at 2.25 metres/second is not quite achieved, and in fact 2.35 metres/second is required at 54 RPM. If the rotor is upgraded to the performance of an NACA 0015 section as shown in Figure No. 3, then the expected performance is shown in Fig. No. 4. This shows that 5 kW is achieved at 2.28 m/sec. and 64 RPM (9"Pulley).

The most important conclusion from these trials is that for unducted vertical axis hydro turbines of the Darrieus type, a high solidity is required. Reviewing the experimental data summarized in Ref. 11.6 together with the results of these trials, it can be concluded that optimum performance is obtained with a solidity of close to 0.2 per blade. It is also concluded that for minimum torque ripple effects and optimum starting characteristics a four bladed rotor is the best choice.

Demonstration of reasonable agreement between model test and full scale trials data gives confidence in predicting performance based on model tests in the water flume. Model trials data, supported by the earlier "VEGA" experiments and Sandia Laboratory experiments, all show that the NACA 0015 foil section is the best choice for Darrieus type turbines and it is recommended that this section should be used for future TOR 5 trials and eventual production units. Further trials will improve the accuracy of the data and confidence in extrapolating the data to larger turbines.

The "B" Series rotor tested used existing foil sections from other projects. The blades used were close to the optimum chord, but the section used for the arms has too small a chord for extended use (i.e. 75 mm (2.95")). A reasonable compromise between minimum hydrodynamic drag of the arms and maximum structural strength is an arm chord of about 67% of the foil chord. Thus for a solidity of 0.81 the blade chord would be 185 mm (7.29") and the arm chord 124 mm (4.88").

Aspects of the TOR 5 project which require further field trials include trials to establish the practical aspects of bringing power ashore by an underwater cable, mooring TOR 5 in a fast current, operating in adverse weather for long periods, and establishing the durability and reliability of the unit over long periods of operation.

6.1.8 Data Accuracy

The velocity was measured from the tow boat using a Loran "C" System which is accurate to + or - 0.1 knots, but it is difficult for the trials crew in the TOR 5 unit to be sure that the speed has stabilized and a towed speed measureing system would give more confidence in the data.

Based on earlier trials experience the turbine was towed about 100 ft. behind the tow boat to minimize wake effects.
The RPM is based on the Thompson and Howe frequency meter which is accurate to + or - 2%. The Dump load percentage reading is also accurate to + or - 2%. The voltage was read using a multimeter with an accuracy of + or - 1%. The ammeter had a range of 75 amps and could not be read accurately in the range of 0 to 10 amps.

6.2 RECOMMENDATIONS

It is recommended that some modifications be carried out based on the results of the trials to date, and then more detailed field trials be conducted including endurance trials in a local river. Once these trials are complete it is proposed that demonstrations be arranged in at least three locations across Canada.

PHASE I TRIALS

6.2.1 Instrumentation Additions and Modifications.

Field type towed Ottmeter or similar instrument for velocity readings. (Electro magnnetic velocity meters have given erratic performance under field conditions. i.e. Cornwell, Sheet Harbour, Allan Water Bridge, Rocky Run, Halifax Harbour etc.).

Ammeter connected to read total generator output, with a range of 25 amps in 1/2 amp intervals, and a mirrored scale.

A voltmeter reading 0 to 300 volts in 5 volt intervals.

A dual range oscilloscope with chart recorder to monitor frequency, waveform and voltage fluctuations. All dial readouts to be set up on a board with a digital clock and date readout plus a chalk board for other data, and a camera with flash for recording of data using high speed black and white film.

6.2.2 Mechanical Modifications

An essential change required is the installation of upgraded winches for the rotor assembly retraction and extension system. For endurance testing in a river site a mooring cable and anchoring or attachment equipment will be required. This will depend on the specific requirements of the site. Replacement of the lower rotor bearing is required.

The feasibility of procuring and fitting a 10.75" (or 11") Dia. pulley should be examined, to give 54 R.P.M., and a 9" pulley to give 64 R.P.M. The current 8" and 10" pulleys give 72 and 58 R.P.M. respectively. Provision should be made to test the rotor blades at + 1.25 deg., + 3 deg. and + 6 deg. incidence.

6.2.3 Electrical System Modifications

Rewire the Ammeter to read total generator output. Adjust the generator voltage control to give 240 volts at 60 Hz instead of 250 volts. Replace the defective TRIAC in the Thompson and Howe load Control unit. Test and function all systems under low speed towing conditions. Monitor gearbox and generator temperatures under extended operating conditions.

6.2.4 Phase I Trials Program

A detail trials program will be drawn up to ensure all aspects of the TOR 5 performance characteristics are investigated. EMR and NRC personnel will attend the final series of trials and review the scope of the trials program and the results.

PHASE II TRIALS

6.2.5 Mechanical and Equipment Modifications

More comprehensive modifications would be carried out followed by further field trials and demonstrations in Nova Scotia, Ontario and British Columbia. Modifications to the rotor assembly would include new blade and arm extrusions, new rotor hub units to allow blade folding, an aluminium rotor shaft with stainless steel sleeves and new self lubricating bearings with grit seals.

Small gunnell mounted outboard motors would be added to allow the TOR 5 unit to be tested and deployed or relocated without the need for a tow boat. The machinery enclosure would be insulated and fitted with an automatic cooling fan. The rotor brake would be modified for solenoid operated fail safe operation.

A canvas cover and sump pump would be added for extended unattended operation.

6.2.6 Electrical System Modifications

A marine battery with onboard charging system would be added to operate the sump pump, navigation lights, rotor brake solenoid, and trouble light for maintenance and nightime operation. Stop/Start controls and some onshore instrumentation readouts would require control cables to run with the power cable. An armoured power, control, instrumentation and mooring cable would be used to ensure safe long life operation of the system and to simplify installation, maintenance and cost.

The electrical system, other than the generator and disconnect switchgear and fuses, and the battery related equipment, would be located in a shoreside box or shed (if available), or in a local power company facility.

6.2.7 Phase II Trials Program

This program would be similar to the Phase I Program, but would incorporate any additional or different instrumentation and parameters that may become evident during the Phase I Trials and the Phase II Modifications.

6.3 PUBLIC AWARENESS

Nova Energy has a continuing interest in public awareness and has presented papers on the VAHT at a number of conferences, including The Energex Conference in Regina, Saskatchawan, in May 1984, and The Offshore Technology Conference in Houston, Texas, in May 1986.

Mr. B. Davis chaired a session on Ocean Energy at the International Ocean Engineering Conference held in October 1987, in Halifax, Nova Scotia. Mr. Davis also presented a paper at this conference on the prospects for using the VAHT in large tidal sites such as the Bay of Fundy.

In meeting the specific terms of this contract Mr. Farrell attended the "Small Hydro Canada 87" conference, held in Burnaby B.C., in March 1987, where he presented a paper on Nova Energy,s work on the floating freeestream Vertical Axis Hydro Turbine, TOR-5. (Refer to Appendix "F").
A precise of this paper was included in the May-June 87 issue of the Solar Energy Society of Canada magazine SOL.

7. DRAWINGS

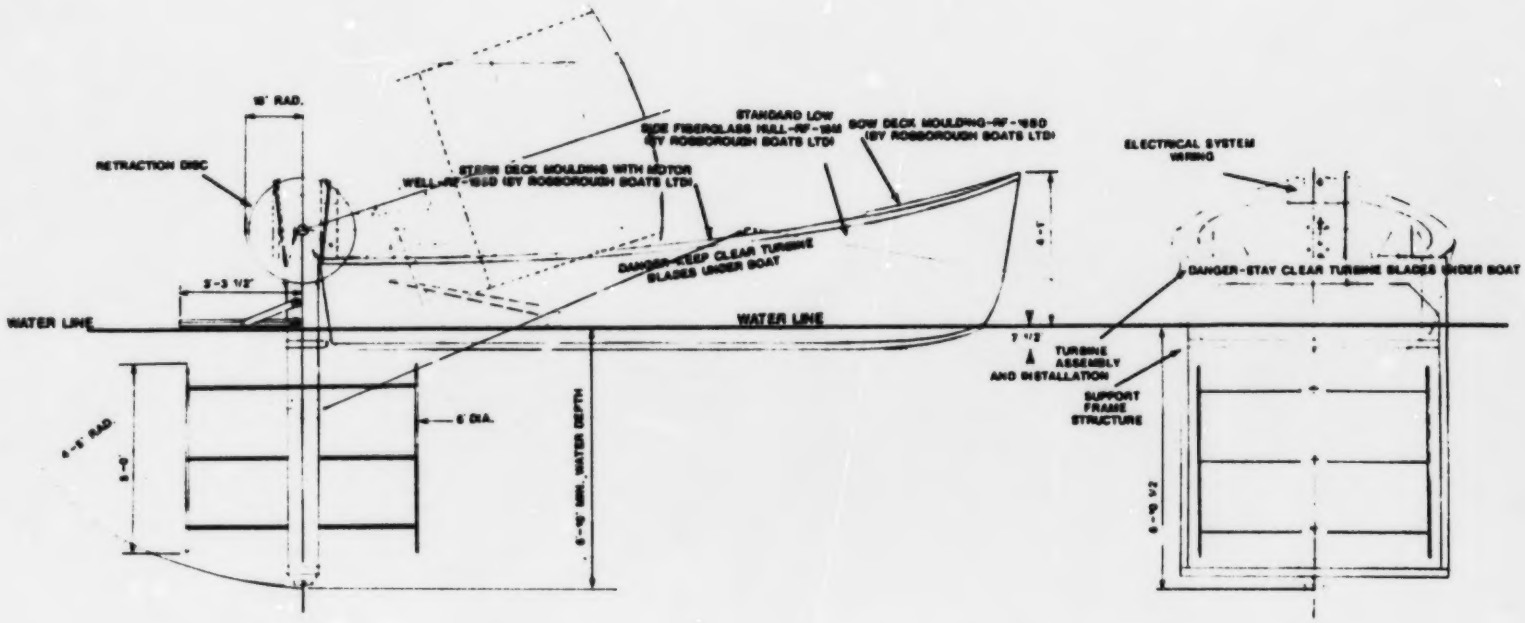
The design and construction drawings used to build the TOR 5 VAHT are listed below.

Drg. No.	Title	Issue No.	No. Sheets
TOR-5-100	General Arrangement	3	1
TOR-5-200	Support Frame Structure	2	2
TOR-5-300	Turbine Assembly Drawings "V" Series Rotor	3	2
TOR-5-350	Rotor Shaft & Bearings Machining & Assembly Details	2	1
TOR-5-360	Rotor Assembly Drawing "B" Series Rotor	1	1
TOR-5-410	Electrical System Wiring Diagram.	2	1
TOR-5-G-001	Hand Brake Geometry	1	1

Total of 9 Drawings

NOTE:- A complete set of drawings are enclosed in the "Original" Report for the Design Authority. All other reports contain a copy of the General Arrangement Drawing TOR-5-100 only.

TOR-5 GENERAL ARRANGEMENT DRAWING



8. PHOTOGRAPHS - CONSTRUCTION, ASSEMBLY AND TRIALS

Photographs were taken of the various stages of construction, assembly and field trials of TOR 5 and are referenced in the report.

40 prints are included in the following nine pages and are briefly described below.

8.1 Frame Structure and Rotor Assembly Details.

8.2 Complete Rotor Support Frame With Folded Rotor Arms and "V"Series blades.

8.3 Low Speed Coupling Installation

8.4 Self Lubricating Thrust Bearing

8.5 & 8.6 "V" Series Rotor Blades in Operating Position

8.7 & 8.8 "V" Series Rotor Blades in Stowed Position

8.9 Machinery Plate With Frame Hinges and Gearbox

8.10 Rotor Assembly Jigs

8.11 Rotor Arm Weld & Drill Jig & Gearbox Alignment Jig

8.12 Hull/Frame Hinge Jig & Rotor Blade Drill Jig

8.13 Thomson and Howe Load Control Governor

8.14 Primary Shore Switch Box

8.15 Shipboard Circuit Breaker and Switch Box

8.16 Demand Loads L3 to L6

8.17 General Stern View with Frame Retracted

8.18 Stern View With Belt Drive Cover In Place

8.19 Bow View showing Towing and Frame Drag Cable Attachment Beam and Fittings

8.20 Gearbox and Generator Installation

8.21 Twin "V" Belt Drive & Frame To Hull Hinge Attachment

8.22 Generator With Retraction Disc ON Right

8.23 Generator Belt Tensioning Arrangement

8.24 Detail of Frame To Hull Hinge Installation

8.25 Junction Box Mounting On Hull

8.26 "V" Series Rotor & Frame Assy. In Vertical Position

8.27 General Stern View of TOR 5

8.28 Loading TOR 5 On A Boom Truck At The Plant

8.29 Unloading TOR 5 at Three Fathom Harbour

8.30 TOR 5 Waiting For The Tide

8.31 TOR 5 Beached At Rocky Run

8.32 TOR 5 Moored Under The Railway Trestle At Rocky Run

8.33 Demonstration Of Stability With Rotor Frame Vertical

8.34 Electrical Equipment On The Railway Trestle

8.35 Pitch Stability With Frame Extended 180 degrees

8.36 View from above shows details of Machinery Enclosure, Frame Structure, Rotor Assembly, Retraction Disc and Frame To Hull Hinges.

8.37 Stern View Shows TOR 5 Configuration With "B" Series Blades

8.38 Rotor Frame, "B" Series Rotor And Frame Support Struts

8.39 View of "B" Series Rotor With Large Blades and Small Arms

8.40 View Showing Welding Of The Arm Support Discs To The Hubs And Bolting Of The Arms To The Discs

NOTE :- THE DESIGN AUTHORITY HAS A COMPLETE SET OF ORIGINAL PHOTOGRAPHS FROM THE DRAFT FINAL REPORT.

9. TABLES

TABLE I - Data Analysis TOR 5 VAHT May 1988

Vk	Va	Vm	Demand kW	Dump %	Dump kW	% Dump Load	Total kW	Hz	Volts Ref.	RPM N	TSR	Ck	Ref. Amps	Total kW
3.75	6.34	1.93	1.00	0	3	0	1.00	60	250.	58.	2.86	.138	5	1.25
3.75	6.34	1.93	2.00	0	3	0	2.00	50	208.	48.	2.38	.276	5	1.04
4.25	7.18	2.19	1.00	.40	3	1.20	2.20	60	250.	58.	2.52	.209	10	3.70
4.25	7.18	2.19	2.00	.40	3	1.20	3.20	55	229.	53.	2.31	.303	10	3.49
4.25	7.18	2.19	3.00	.40	3	1.20	4.20	50	208.	48.	2.10	.398	10	3.28
4.50	7.61	2.32	4.00	.25	3	.75	4.75	50	208.	48.	1.98	.379	15	3.88

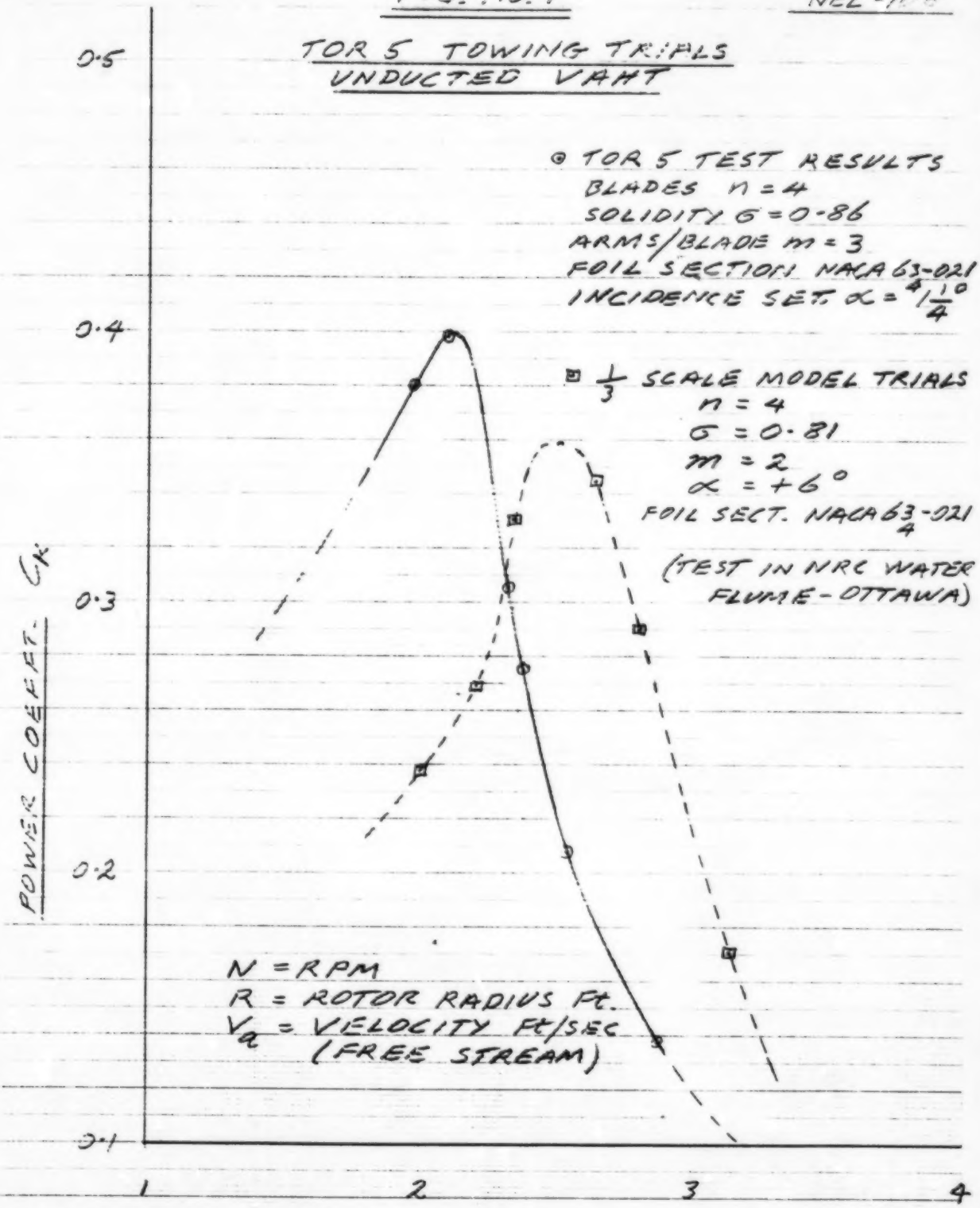
TABLE II Performance Calcs. TOR 5 VAHT May 1988

		58 RPM --------->			54 RPM --------->		
Vm	Va	TSR	Ck	kW	TSR	Ck	kW
1.75	5.74	3.17	.102	.55	2.95	.125	.67
2.00	6.56	2.78	.152	1.22	2.58	.193	1.56
2.25	7.38	2.47	.233	2.67	2.30	.312	3.57
2.37	7.78	2.34	.290	3.88	2.18	.388	5.19
2.50	8.20	2.22	.364	5.72	2.07	.396	6.22
2.60	8.53	2.14	.398	7.04	1.99	.381	6.74
2.75	9.02	2.02	.386	8.07	1.88	.362	7.57
3.00	9.85	1.85	.354	9.62	1.72	.323	8.78

10. FIGURES

FIG. NO. 1 NEL-108

TOR 5 TOWING TRIALS
UNDUCTED VAWT



● TOR 5 TEST RESULTS
BLADES $n = 4$
SOLIDITY $\sigma = 0.86$
ARMS/BLADE $m = 3$
FOIL SECTION NACA 63-021
INCIDENCE SET. $\alpha = +1\frac{1}{4}^\circ$

□ $\frac{1}{3}$ SCALE MODEL TRIALS
$n = 4$
$\sigma = 0.81$
$m = 2$
$\alpha = +6^\circ$
FOIL SECT. NACA $63\frac{3}{4}$-021

(TEST IN NRC WATER FLUME - OTTAWA)

N = RPM
R = ROTOR RADIUS Ft.
V_a = VELOCITY Ft/SEC (FREE STREAM)

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FIG. No. 2.

MODEL TEST DATA - NACA 0015 SECTION

UNDUCTED RAHT

$n = 4$
$G = 0.81$
$m = 2$
$\alpha = 6°$

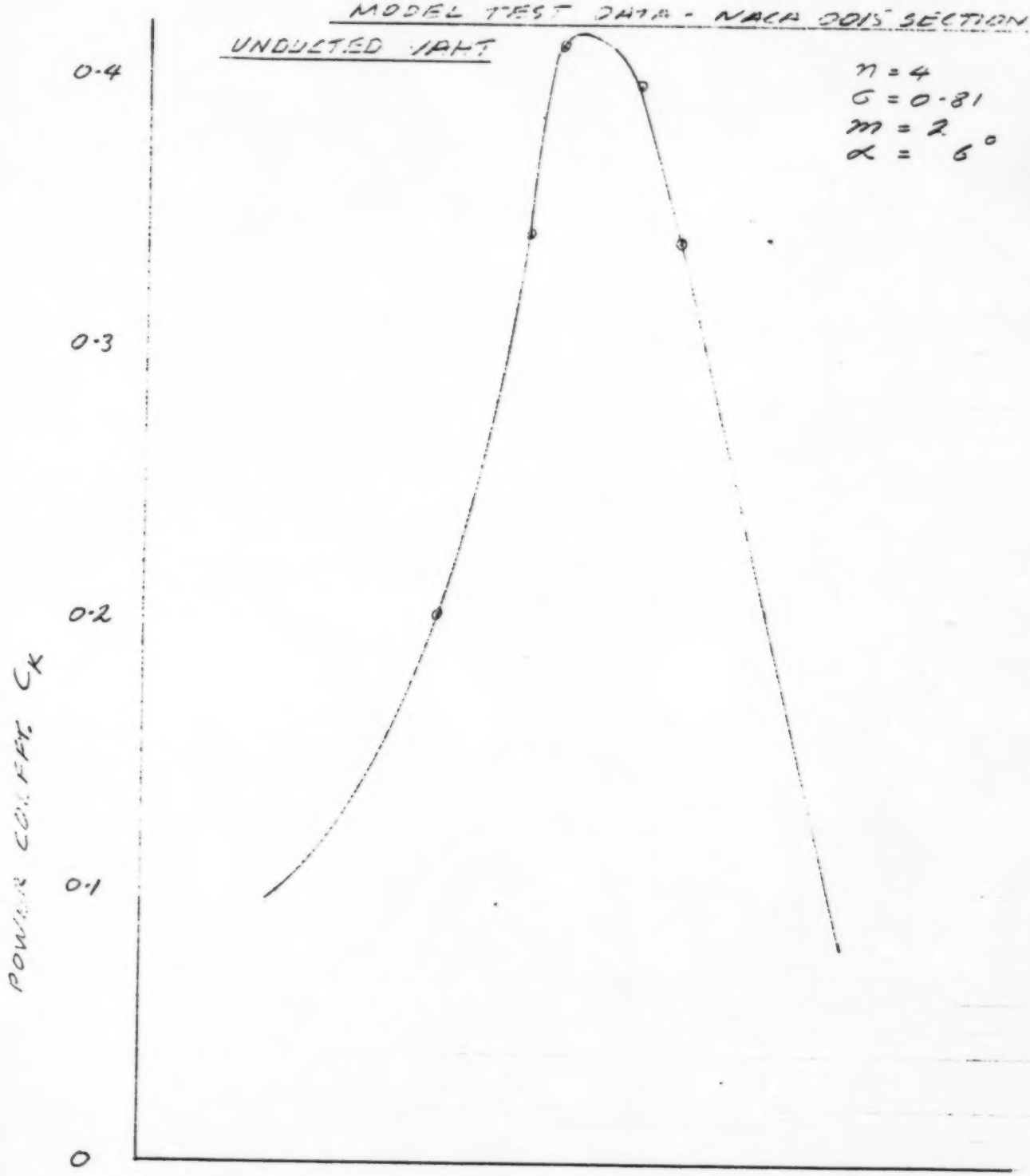

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FIG. No. 3 NEL-108

TOR 5 PERFORMANCE BASED ON TOWING TRIALS DATA UNDUCTED VAHT

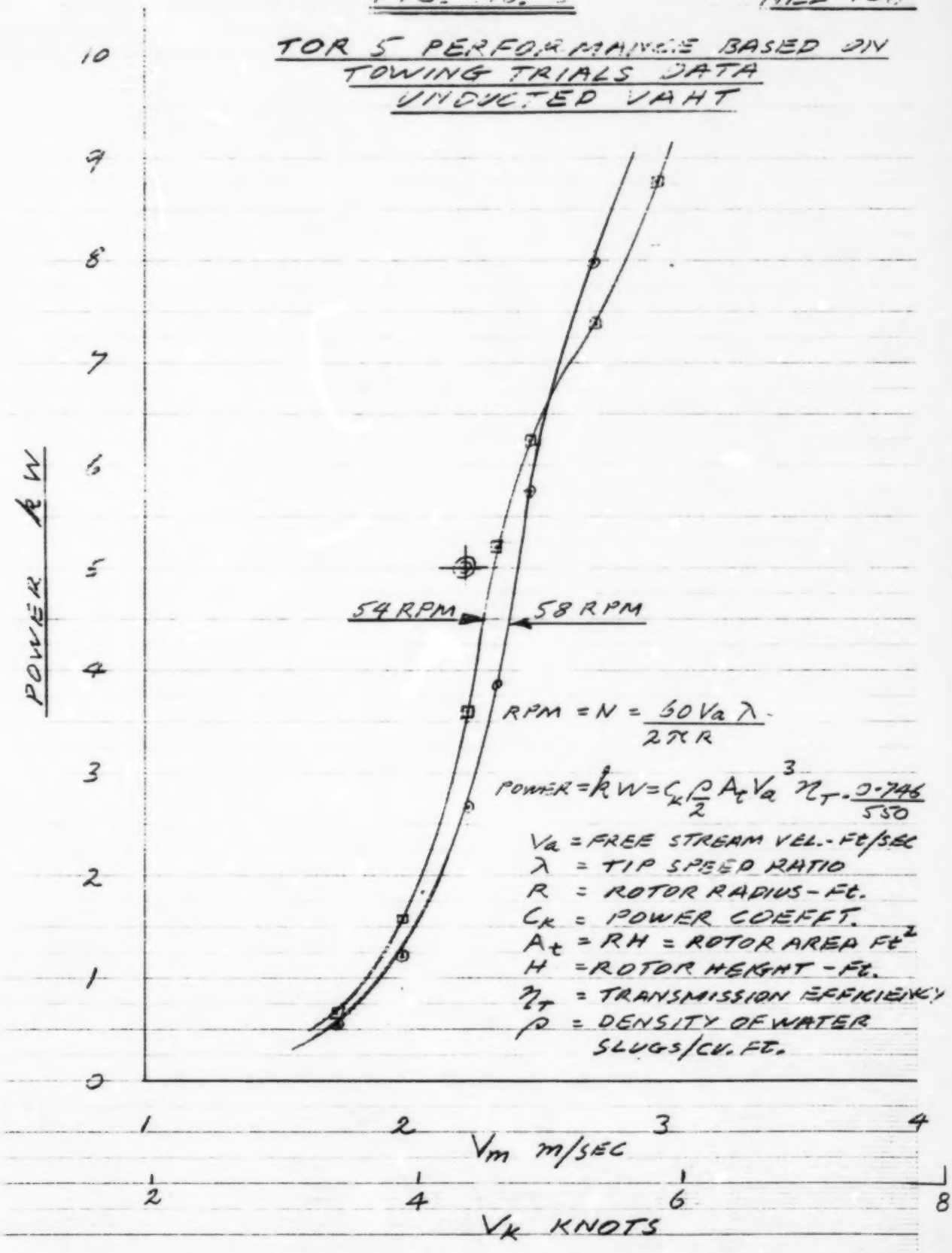

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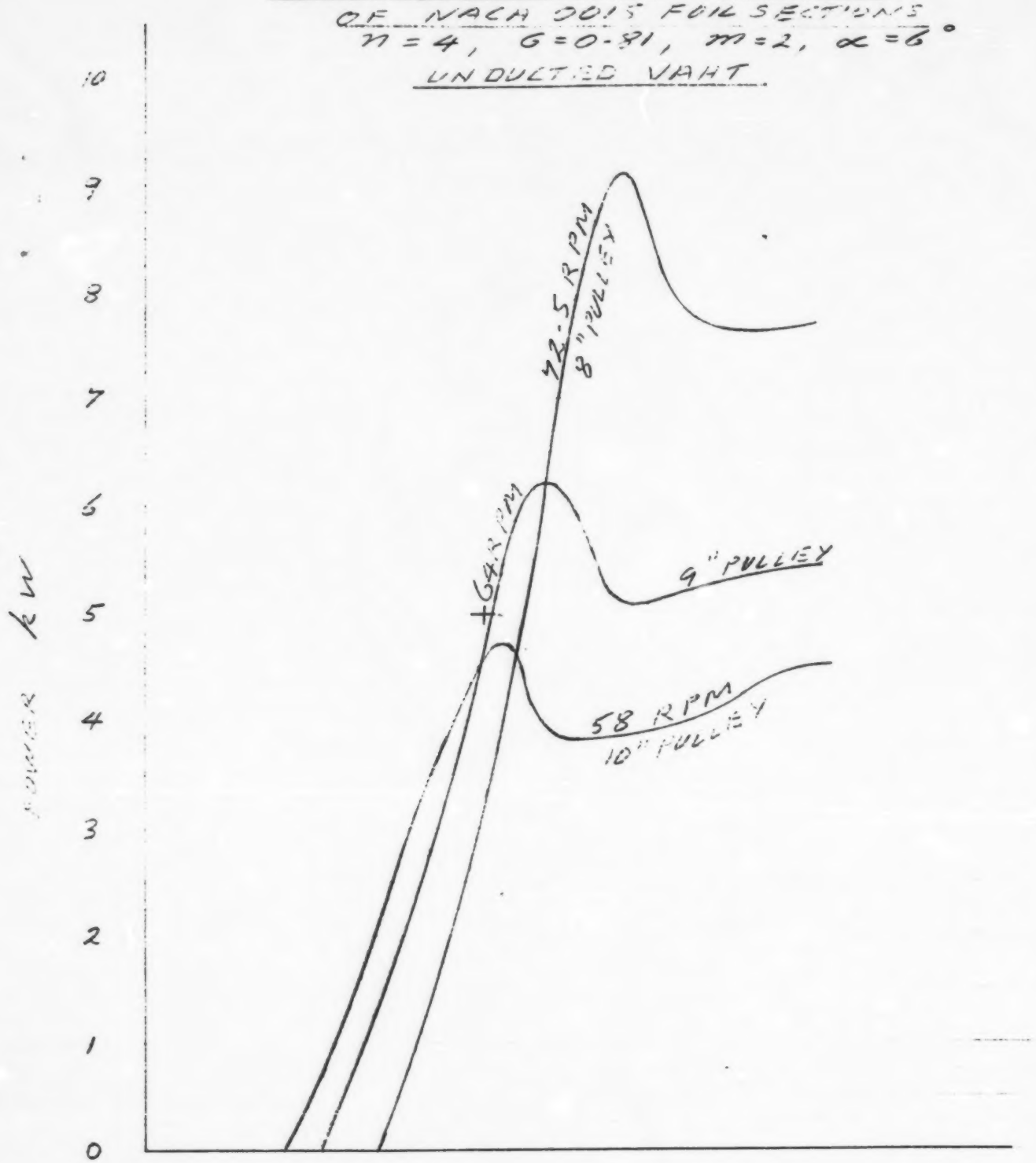
FIG. No. 4

PREDICTED TOP PERFORMANCE
BASED ON NRC FLUME TRIALS
OF NACA 0015 FOIL SECTIONS
$n = 4$, $G = 0.81$, $m = 2$, $\alpha = 6°$
UNDUCTED VAWT.



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